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MULTIPLE PLATE PENETRATION MODEL 3 (MPPM3) REVIEW

Final Report

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Project Team

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Disclaimer

The contents of this report and the processes and data that are embedded in the program reflect the views of the above named contractors and do not necessarily reflect the official view or opinions of the Department of National Defence.

EXECUTIVE SUMMARY

The lethality of ammunition, and/or the effectiveness of armour can be assessed by the penetration (or perforation) performance of the ammunition, and by the nature of the "debris" that results on the "inside" of the armour following a threat/armour interaction. The "debris" comprises the residual projectile and armour fragments generated during the penetration event. These fragments are referred to as behind-armour debris or BA debris.

The Debris Characterisation and Modelling (DeCaM) software was developed to quantitatively characterise experimentally captured BA-debris data and model or predict the characteristics of BA-debris clouds generated in ballistic penetration events. Both the BA-debris characterisation and modelling require information describing the residual penetrator mass and velocity. The Multiple Plate Penetration Model (MPPM3) software was adopted by DeCaM to estimate residual penetration characteristics.

The following report presents a review of the Multiple Plate Penetration Model (MPPM3) software and its documentation. The review describes the MPPM3 software data requirements and output formats. In addition, the process by which the residual penetrator characteristics are estimated is described in terms of a pseudo code software description. The information in this report is published in the current document as a stand-alone report and as part of the project report describing improvements to the DeCaM software.

ABSTRACT

The Debris Characterisation and Modelling (DeCaM) software was developed to quantitatively characterise experimentally captured BA-debris data and model or predict the characteristics of BA-debris clouds generated in ballistic penetration events. Both the BA-debris characterisation and modelling require information describing the residual penetrator mass and velocity. The Multiple Plate Penetration Model (MPPM3) software was adopted by DeCaM to estimate residual penetration characteristics. In order to implement this software its operation and characteristics needed to be reviewed. The following report describes the MPPM3 software data requirements and output formats. In addition, the process by which the residual penetrator characteristics are estimated is described in terms of a pseudo code software description. The information in this report is published in the current document as a stand-alone report and as part of the project report describing improvements to the DeCaM software.

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1.0 INTRODUCTION

MPPM3 is the third version of the Multiple Plate Penetration Model software, MPPM. The software / model predicts variations in projectile velocity, mass, orientation and direction for spin-stabilised projectiles penetrating spaced target elements.

The program was prepared by Jerome D. Yatteau and Richard H. Zernow (1990) at Applied Research Associates Inc. for the Naval Surface Warfare Centre.

The objective of this review is to develop an understanding of the MPPM3 software to allow its inclusion in the DeCaM software as a ballistic penetration prediction module. This report has been prepared to describe the MPPM3 software in terms of its structure, capabilities and limitations. The report also outlines both the user supplied and resident material property data used by the MPPM3 penetration model.

The sections which follow describe the findings of this review in terms of the:

- Capabilities, Limitations and Definitions (Section 2.0),
- MPPM3 Modelling Data and Parameters (Section 3.0),
- MPPM3 Output (Section 4.0), and
- Software Description - Structure and Operation (Section 5.0).

2.0 CAPABILITIES, LIMITATIONS AND DEFINITIONS

The MPPM3 software / model was assembled based on a variety of research efforts to model ballistic penetration events. The model was developed to provide residual penetrator characteristics during and after penetration for spin-stabilised projectiles. The software and model operate based on a variety of semi-empirical impact momentum conservation formulations, developed using imperial units of measurement. The model includes facilities to:

- predict whether target penetration occurs or not,
- calculate residual penetrator velocity, mass, orientation and direction during and after the penetration of spaced element target systems, and
- predict the erosion, deformation or break-up of projectiles during the penetration event and provide velocity, mass, and trajectory data for the resulting fragments.

The MPPM3 software system does not contain any numerical data entry limitations. Error trapping is confined to user responses to software data entry prompts, data file names and checking alphabetic codes for model parameters such as target components and materials. The software does contain a "help" menu to aid the user in selecting appropriate codes for model parameters such as target components and materials.

2.1 Projectile Material and Geometry

The authors of the software indicate that the MPPM3 model is capable of handling a variety of projectile materials including depleted uranium, tungsten alloys, steel and other ductile metals. It should be noted that the projectile penetration, erosion and break-up calculations differentiate between projectile materials based on their geometry, specific weight, Brinell hardness and ultimate strength.

Projectile geometries accommodated by the software include any combination of cylindrical base section and a truncated cone nose section, as shown in Figure 2.1. The MPPM3 software can accommodate extreme projectile geometries including: flat-ended cylinders and projectiles with pointed conical noses. It should be noted again that MPPM3 is only applicable to spin-stabilised projectiles and fin-stabilised projectiles are not explicitly dealt with.

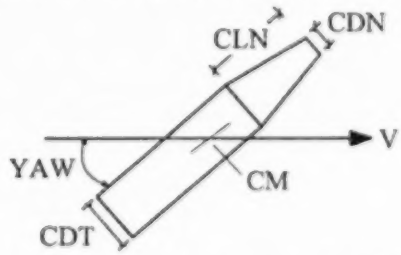


Figure 2.1: Projectile Geometry Definitions

The user may input shape factors to account for the influence of nose shape on the effective mass of target material accelerated by the projectile. The two shape factors CSF and PIF are projectile nose shape factors applied to the plate plug mass in residual velocity and residual mass calculations, respectively. It is indicated that unless experimental penetration data is available to tune the model the given default values (see Section 3.0) should be used.

Although it has not been confirmed, it is suspected that the following equations may be used to estimate the projectile shape factors used in the software:

$$CSF = \frac{M_{cyl}}{M_p} \quad \text{and} \quad PIF = \frac{M_{cyl\ cone} - M_{p\ cone}}{M_{cyl}\ cone}$$

where:

M_p	Projectile mass
$M_{p\ cone}$	Mass of conical frustum portion of projectile
M_{cyl}	Mass of smallest cylinder enclosing projectile
$M_{cyl\ cone}$	Mass of smallest cylinder enclosing conical frustum potion of projectile

Shape factors for the software default projectile, a 20mm PHALANX MARK 68, are given in Section 3.0.

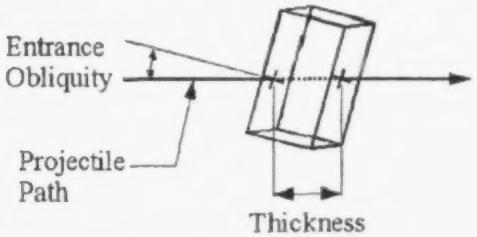
2.2 Target Configuration

Target systems in the MPPM3 software are defined in terms of target system components and their materials. The four target component types available in the MPPM3 software include:

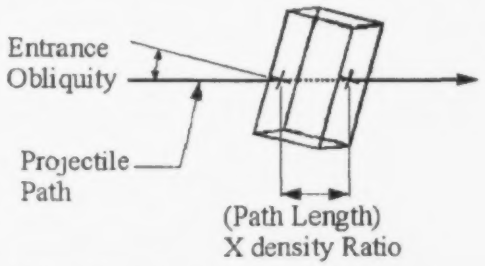
- plate components (P1),
- single plate representations of volumetric components (V1),
- fluid or non-coherent material filled volumetric components (V2), and
- 18 plate volumetric component representation of avionics "black boxes" (V3 and V4).

The difference between volumetric components V3 and V4 involves the definition of average plate density ratio. All 18 of the plates within volumetric component V3 have the same average volumetric plate density, whereas, those in volumetric component V4 are randomly assigned a plate density between 80 and 140% of the average plate density value. The random plate density value is used to reflect the typical variation in component density along various shot lines. It is not stated in the user manual, but it is likely that the random numbers are uniformly distributed, since they are generated directly from the operating system random number generator based on a user supplied seed value.

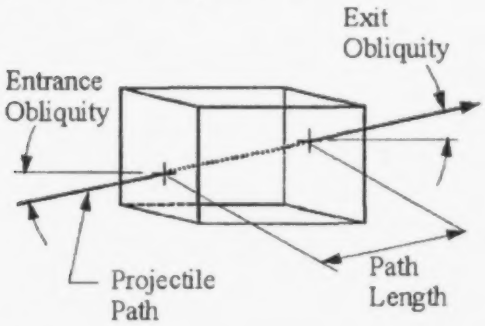
The parameters used to describe the four target system component types are shown in Figure 2.2.



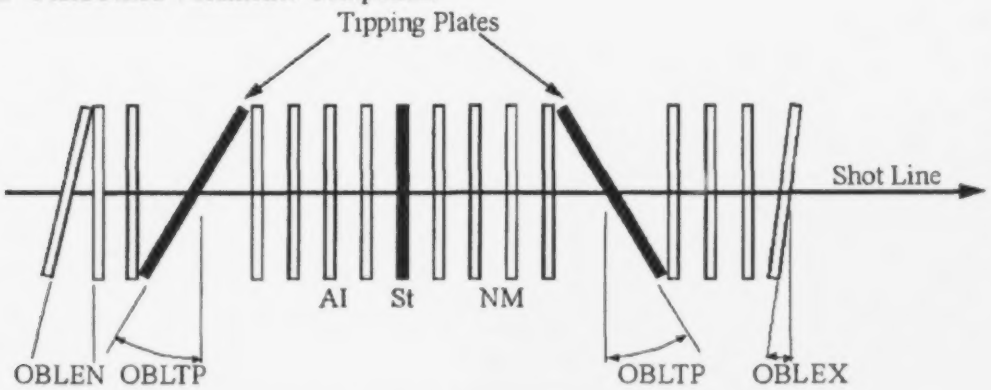
a) P1 - Plate Component Definition



b) V1 - Plate Analogy for a Volumetric Component (Component path length is as defined for component V2)



c) V2 - Fluid Filled Volumetric Component



d) V3 and V4 Volumetric Component - 18 Plate Avionics Component Representation

Figure 2.2: Target Component Definition Parameters

The difference between target components V1 and V2, both of which may model a fluid or non-cohesive filled volume, is the means of calculating the penetrator residual velocity and erosion. Residual velocity for component V1 is based on a plate penetration model, whereas, the residual velocity for component V2 is calculated based on the projectile drag coefficient, fluid or material density and a standard exponential velocity decay function. It is also assumed that no projectile erosion occurs during the penetration of a target of component type V2.

The target components are made up of a variety of material types including: steel, aluminium, woven-roving laminated fibreglass panels (GRP and DORON), kevlar laminated fabric panels, laminated XP plastics, LEXAN, ceramic-faced composites and non-coherent materials (fluids). The mechanical properties of each material type are defined within the MPPM3 software, as discussed in Section 3.0.

The software includes a default target, an S2M2 plate array, comprised of 18 plates as described in Section 3.0.

2.3 Ballistic Penetration Model

The penetration events handled by the MPPM3 software are those that include spin-stabilised projectiles, target systems described by the four MPPM3 target components and the projectile/target encounter parameters described in Figure 2.3.

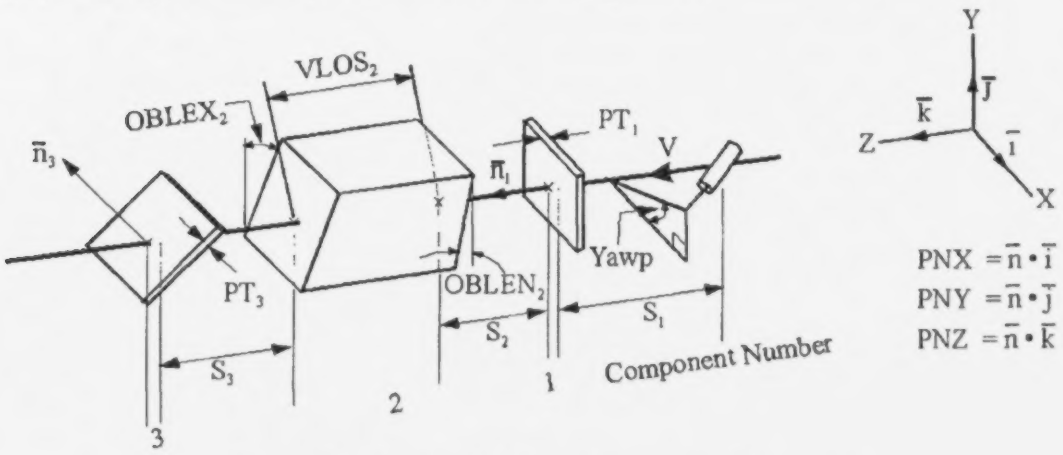


Figure 2.3: Projectile / Target Encounter Parameters

The MPPM3 software allows the user to either select the target penetration mode or allow the software to automatically determine the target penetration mode. The user may select from: 1) a thick plate model (TPPM), 2) a thin plate (plate plug) model (PLUG), or 3) use the default combined model that interpolates between the thick and thin plate model predictions depending on impact velocity and plate thickness.

When using either the thick plate or the combined model, the user has the option of having the calculation results displayed in dimensional (default) or non-dimensional formats. The non-dimensional data representation, in-general, non-dimensionalises linear measures based on the diameter of a circular area equal to the projectile's presented area, whereas, velocity based data is non-dimensionalised with the projectile impact velocity.

3.0 MPPM3 MODELLING DATA AND PARAMETERS

In this section the user supplied "data" and modelling "parameters" embedded in the MPPM3 software are described. Ideally, upper and lower limits on the values associated with both data and parameters would be defined. This is not the case in the MPPM3 software, therefore, based on a review of the published research efforts leading to the development of these models and some common sense, minimum and maximum values have been suggested for each data and parameter. In addition, the program variable and array name associated with each data value has been noted along with any default values to facilitate incorporation of this software into other programming efforts.

3.1 MPPM3 User Defined Data

The user supplied data is arranged into the three groups: 1) C - projectile data, 2) E - encounter data and 3) P - target system data. After the user supplies the C, E and P data values they are stored into the CIN(), EIN() and PIN() input data arrays, respectively. As calculations are completed these data values are transferred to the working variable names shown in Tables 3.1, 3.2 and 3.3. Each of the user defined data description tables includes a default value and proposed limits (upper and lower bounds) on their numerical values. These values are proposed for use in data entry error trapping when MPPM3 is incorporated into the DeCaM software.

The projectile data describes the physical properties of the projectile of interest. The default values shown in Table 3.1 are based on a 20mm Phalanx projectile. The projectile data includes two shape factors, VR (CSF) and MR (PIF). The VR shape factor is used in the plate/plug mass residual velocity calculation, whereas, the MR ratio is used in the plate/plug mass residual mass calculation. It is suggested, in the MPPM3 documentation, that a value of 1.0 be assumed for the VR shape factor if it has not been experimentally defined. The documentation also suggests that a value of 0.5 or 1.0 be assumed for the MR shape factor for pointed and flat ended projectiles, respectively, if appropriate values have not been experimentally derived. Some additional information on the basis for establishing these shape factor values is given in Section 2.1.

The drag coefficient, in Table 3.1, is only required when the projectile penetrates a volumetric target component type V2 (see Section 2.2 for additional information). The drag coefficient is used to calculate the projectile velocity reduction in the fluid or non-coherent material contained in a V2 target component. It is noted that the projectile is assumed to move freely in air with no velocity reduction.

Table 3.1: Projectile (C) Data Summary

Data		Default Value	Variable Name	Array Name	Minimum Value	Maximum Value
Weight	[grains]	1 080.0	CM	CIN(1)	> 0.0	15 000.0
Base Diameter	[in]	0.47	CDT	CIN(2)	.2	1.5
Nose Length	[in]	0.577	CLN	CIN(3)	0.0	4.0
Nose Diameter	[in]	0.247	CDN	CIN(4)	0.0	1.5
Specific Weight	[lbs/in^3]	0.667	CRHO	CIN(5)	> 0.0	1.0
Brinell Hardness		285.0	CBHN	CIN(6)	10	1 000
Ultimate Strength	[psi]	133 500.0	CUS	CIN(7)	500	400 000
Shape Factor[1]	(VR)	1.2	CSF	CIN(8)	1.0	5.0
Shape Factor[1]	(MR)	0.4	PIF	CIN(9)	0.1	1.0
Drag Coefficient		1.0	CCD	CIN(10)	0.0	4.0

[1] Penetration (mass to volume) related shape factors

The encounter data listed in Table 3.2 describes the kinematics of the ballistic impact event. The initial projectile yaw (YAW) and yaw plane angle (YAWP) describe the orientation of the projectile with respect to the shot line, as shown in Figure 2.3. While the yaw angle describes the rotation of the projectile about its centroid, with respect to the shot line (z-axis), the yaw plane angle describes the rotational position of the projectile about the shot line (z-axis) with respect to the x-axis.

Table 3.2: Encounter (E) Data Summary

Data		Default Value	Variable Name	Array Name	Minimum Value	Maximum Value
Impact Velocity	[ft/sec]	6 000.0	V	EC(1)	> 0.0	10 000.0
Spin Rate	[rad/sec]	13 800.0	SPIN	EC(2)	5 000	25 000.0
Initial Yaw	[deg]	3.0	YAW	EC(3)	0.0	60.0
Yaw Plane Angle	[deg]	270.0	YAWP	EC(4)	0.0	180.0
First Impact Velocity	[ft/sec]	6 000.0	VSTART	--	> 0.0	10 000.0
Last Impact Velocity	[ft/sec]	6 000.0	VEND	--	> 0.0	10 000.0
Velocity Increment	[ft/sec]	1.0	VINC	--	> 0.0	10 000.0

The MPPM3 ballistic penetration software may be operated in batch mode which allows the penetration event to be modelled for a range of impact velocities ranging from an upper (VSTART) to a lower (VEND) bound impact velocity. The number of steps in the batch ballistic penetration modelling process is calculated based on the velocity increment value (VINC) provided by the user.

Table 3.3 outlines the data required to describe a target system. Since a target system or array may include more than one component, the NPLATE input data variable is used to identify the number of target system components which need to be described by the other data variables. Most of the target data is read from a file into a two dimensional array, PIN(I,#), whose indices refer to the target system component number and data item, respectively. Many of the target data variables are described in Figures 2.2 and 2.3.

Table 3.3: Target (P) Data Summary

Data	Variable Name	Array Name	Minimum Value	Maximum Value
Number of Target Components	NPLATE	--	1	20
Z-Axis Component Spacing [in]	S	PIN(I,1)	> 0.0	20.0
Component Type	PTYP	PIN(I,2)	--	--
Material Code	PMTL	PIN(I,3)	--	--
Brinell Hardness	PBHN	PIN(I,4)	10.0	1 000.0
Density Ratio	VRHOR	PIN(I,4)	0.1	1.0
X-Dir. Plate Normal Cosine	PNX	PIN(I,5)	0.0	0.5
Entrance Obliquity [deg]	OBLEN	PIN(I,5)	0.0	60.0
Y-Dir. Plate Normal Cosine	PNY	PIN(I,6)	0.0	0.5
Exit Obliquity[7] [deg]	OBLEX	PIN(I,6)	0.0	60.0
Z-Dir. Plate Normal Cosine[8]	PNZ	PIN(I,7)	0.0	0.5
Tipping Plate Obliquity [deg]	OBLTP	PIN(I,7)	0.0	60.0
Plate Normal Thickness [in]	PT	PIN(I,8)	> 0.0	2.0
Line-of-Sight Path Length [in]	VLOS	PIN(I,8)	> 0.0	60.0
Min Ricochet Obliquity[10] [deg]	RICOBL	--	0.0	90.0
Random No Generator Seed	RANDM	--	0.0	1 000.0
Penetration Model Print Flag	MTPPM	--	--	--

Several of the data values described in Table 3.3 share the same PIN(I,#) array location (e.g. PBHN and VRHOR). These data are mutually exclusive in that they are used to represent material properties for differing materials or they allow different systems of measurement to be used to describe their values. The following points describe the overlapping data variables:

- PIN(I,4) - Brinell hardness (PBHN) is collected for steel (ST) or aluminium (AL) plates, whereas, material density ratio (VRHOR) is used for volume mode components. For V1, V3 and V4 components, VRHOR is the ratio of the average component density to the density of the material corresponding to the input value of PMTL. For V2 components, VRHOR is the ratio of the density of non-coherent materials or fluids to the density of water (specific gravity).
- PIN(I,5) & PIN(I,6) - Entrance and exit obliquity (OBLEN/OBLEX) are entered in place of the *X*- and *Y*-direction plate normal cosines (PNX / PNY), as shown in Figures 2.2 and 2.3, for volumetric components. OBLEN determines the single plate obliquity for V1 components. OBLEN and OBLEX are used for obliquities of the first and last plates of V3 and V4 components. OBLEN and OBLEX are ignored for V2 components.
- PIN(I,7) - Tipping plate obliquity (OBLTP), see Figure 2.2, is entered in place of the *Z*-direction plate normal cosine (PNZ), as shown in Figure 2.3, for volumetric components V3 and V4.
- PIN(I,8) - The line-of-sight path length (VLOS), as shown in Figure 2.2, is entered for volumetric components, whereas the plate normal thickness (PT) is entered for plate components.

The last three target data variables, RICOBL, RAND and MTPPM, are not associated with a particular target system component and are thus not held in the data entry array PIN(I,#). RICOBL is the minimum impact obliquity at which the MPPM3 ricochet model is invoked if the impact velocity is less than the ballistic limit velocity for a particular plate. If a value greater than or equal to 90 degrees is entered for RICOBL, then the ricochet model will not be used. RAND is a seed for the random number generator used in V4 volumetric components to compute shot line areal densities (see Section 2.2 for more details on the differences between component types V3 and V4). The simulated results will always be the same for a given random number seed value. MTPPM is used in MPPM3 essentially as a flag to indicate whether the multiple thick plate penetration model (MTPPM) should printout results after each component or plate in the model is penetrated to develop a projectile velocity, position, etc.. time history. A value MTPPM = 0 will suppress printing, while a value of 1 will trigger the detailed printout.

The default data for the target system is S2M2 18 plate target array. The default data values for this target system are shown in Table 3.4 below.

Table 3.4: Parameters for S2M2 18 Plate Array

	S Element Spacing [in]	**PTYP** Element Type	**PMTL** Material Code	**PBHN** Brinell Hardness	**PNX** X-Dir Plate Normal Cosine	**PNY** Y-Dir Plate Normal Cosine	**PNZ** Z-Dir Plate Normal Cosine	**PT** Thickness [in]
1	0.00	P1	AL	120.0	0.00	-0.707	0.707	0.125
2	11.50	P1	AL	120.0	0.00	0.00	1.00	0.190
3	2.23	P1	AL	120.0	0.00	0.00	1.00	0.375
4	2.23	P1	AL	120.0	0.00	0.00	1.00	0.375
5	2.23	P1	AL	120.0	0.00	0.00	1.00	0.500
6	2.23	P1	AL	120.0	0.00	0.00	1.00	0.125
7	5.00	P1	AL	120.0	0.00	0.00	1.00	0.125
8	1.63	P1	AL	120.0	0.00	0.00	1.00	0.125
9	1.63	P1	AL	120.0	0.00	0.00	1.00	0.125
10	1.63	P1	AL	120.0	0.00	0.00	1.00	0.125
11	1.63	P1	AL	120.0	0.00	0.00	1.00	0.125
12	1.63	P1	AL	120.0	0.00	0.00	1.00	0.125
13	1.63	P1	ST	120.0	0.00	0.00	1.00	0.125
14	1.63	P1	ST	120.0	0.00	0.00	1.00	0.125
15	1.63	P1	ST	120.0	0.00	0.00	1.00	0.125
16	2.50	P1	AL	120.0	0.00	0.00	1.00	0.125
17	8.50	P1	AL	120.0	0.00	0.00	1.00	0.125
18	8.50	P1	AL	120.0	0.00	0.00	1.00	0.125

3.2 MPPM3 Embedded Parameters

Aside from the default target, encounter and projectile default data values, the MPPM3 software contains a library of target material properties. Table 3.5 lists the 15 materials included in the nominal material property database along with their material codes (PMTL).

Table 3.5: Target Component Material Codes

Material	Code
Aluminium	AL
Steel	ST
Titanium	TI
Copper	CU
Magnesium	MG
Lead	PB
GRP	GR
Doron	DO
Kevlar	KV

Material	Code
XP Plastic	XP
Lexan	LX
Ceramic (Al_2O_3) with woven-roving (GRP or Doron) backing	CW
Pyrex with woven-roving (GRP or Doron) backing	PW
Ceramic (Al_2O_3) with Kevlar backing	CK
Non-Coherent Material (fluid)	NM

The database of target materials contains both metallic and non-metallic materials whose behaviour to ballistic impact or mechanical properties are described by differing parameters. The parameters used to describe metallic and non-metallic plate materials are listed in Tables 3.6 and 3.7, respectively. Many of the listed metallic material properties have been related to the hardness of the material through some empirical equations. While the MPPM3 code is sufficiently clear to apply at this time it would be desirable to:

- determine the physical material properties which are represented by each parameter variable name used in the algorithms, and
- identify the range of validity of the empirical relationships which are used to evaluate parameters based on hardness.

Table 3.6: Metallic Target Material Property Definitions

Parameter		Variable Name	Relationships With Other Properties[1]
Unit Weight	[lb/in^3]	PRHO	
Bulk Modulus	[psi]	PBM	
Regressed from Exp.[2]		PBB	
C_τ[3]	[ft/sec]	PCTAU	1) PCTAU = -0 0054*PBHN^2 + 2 46*PBHN + 984 2) PCTAU = -0 0203*PBHN^2 + 12 53*PBHN + 604
Regressed from Exp.[4]		PCS	3) PCS = -0 0896*PBHN^2 + 26 48*PBHN – 57.58 4) PCS = 0 00131*PBHN^2 + 3 02*PBHN + 2191
Regressed from Exp.[4]		PBS	5) PBS = 0.725 – 0 00035*PBHN
Regressed from Exp.[4]	[ft/sec]	PCB1	6) PCB1 = 0.0164*PBHN^2 – 1.155*PBHN + 430 7) PCB1 = -0.0295*PBHN^2 + 17.25*PBHN + 2110
Regressed from Exp.[4]	[ft/sec]	PCB2	8) PCB2 = -0 107*PBHN^2 + 9 767*PBHN + 4104 9) PCB2 = 2 258*PCB1
Regressed from Exp.[4]		PK	10) PK = -0.0146*PBHN^2 + 1 425*PBHN + 488

[1] Brinell Hardness (PBHN) is a user supplied data for steel and aluminium plates

[2] Likely an experimentally derived coefficient regressed to aid in the determination of normal incident limit velocities, therefore has no physical meaning.

[3] Correction factor to correct for steel and aluminium hardness in calculating V50.

[4] Likely an experimentally derived coefficient regressed to aid in the determination of limit velocities, residual and shatter velocities, therefore has no physical meaning.

Table 3.7: Non-Metallic Target Material Property Definitions

Parameter	Variable Name	Relationships With Other Properties
Regressed from Exp.[1]	PKS	
Regressed from Exp.[1]	PAS	
Regressed from Exp.[1]	PKB	
Regressed from Exp.[1]	PAB	
Average Density [lb/ft^3]	PRHOF	
Unit Weight [lb/ft^3]	PRHO	11) PRHO = PRHOF/1728

[1] Likely an experimentally derived coefficient regressed to aid in the determination of limit velocities, residual and shatter velocities, therefore has no physical meaning.

Based on the material property relationships presented in Tables 3.6 and 3.7, the default mechanical properties contained in MPPM3 for metallic and non-metallic materials are shown in Tables 3.8 and 3.9, respectively.

Table 3.8: Target Metallic Material Property Parameter Summary*

Material	PBHN	PRHO	PBM	PCTAU	PCS	PBS	PCB1	PCB2	PBB	PK
Aluminium	120	0.1	10.E6	1201 (eq-1)	1830 (eq-3)	0.61	528 (eq-6)	3735 (eq-8)	1.75	449 (eq-10)
Steel	150	0.283	23.E6	2027 (eq-2)	2673 (eq-4)	0.67 (eq-5)	4034 (eq-7)	9108 (eq-9)	0.61	0.0
Titanium	--	0.16	18.E6	1450	2660	0.75	1880	4700	1.0	350
Copper	--	0.32	19.E6	750	1424	0.65	913	1896	0.65	0.0
Magnesium	--	0.065	4.2E6	840	561	0.65	360	747	0.65	0.0
Lead	--	0.41	2.E6	100	2260	0.65	1450	3010	0.65	0.0

* Equations relate to material property parameter definitions (Table 3.6)

Table 3.9: Target Non-Metallic Material Property Parameter Summary*

Material	PKS	PAS	PKB	PAB	PRHOF	PRHO[1]
GRP	2725	0.72	1450	0.81	127	0.073
Doron	2725	0.72	1450	0.81	127	0.073
Kevlar	2410	0.38	1600	0.67	80	0.046
XP Plastic [2]	2410	0.38	1450	0.58	57	0.033
Lexan	2200	0.59	1600	0.67	80	0.046
Ceramic/Woven Backing	-1.0	-1.0	2100	1.0	181	0.105
Pyrex/Woven Backing	-1.0	-1.0	1950	1.0	138	0.080
Ceramic/Kevlar Backing	-1.0	-1.0	1700	1.0	156	0.090

[1] Based on equation presented in Table 3.7

[2] Unknown material type, possibly Experimental Plastic

3.3 MPPM3 Input File Formats

As will be discussed in Section 5.0, MPPM3 may be run in an interactive mode using the MPPM3 pre-processor prompts to collect the required input data (see Section 3.1) or the program may be run with user generated input files. The input file is a space delimited ASCII file of the form shown in Figure 3.1. The data input variable names are used in Figure 3.1 to illustrate the location of data within the input file. The variable names and ranges of acceptable value are described in Section 3.1. All of the input data values are real numbers with the exception of NPLATE and MTPPM which are integers.

Title Line						
CIN(1)	CIN(2)	CIN(3)	CIN(4)			
CIN(5)	CIN(6)	CIN(7)	CIN(8)	CIN(9)	CIN(10)	
EC(1)	EC(2)	EC(3)	EC(4)			
NPLATE	MTPPM	RICOBL	RANDM			
PIN(I,1)						
PIN(I,2)	PIN(I,3)	PIN(I,4)	PIN(I,5)	PIN(I,6)	PIN(I,7)	PIN(I,8)
PIN(I+1,1)						
PIN(I+1,2)	PIN(I+1,3)	PIN(I+1,4)	PIN(I+1,5)	PIN(I+1,6)	PIN(I+1,7)	PIN(I+1,8)
•						
•						
•						

Figure 3.1: MPPM3 Input File Format

The input file illustrated in Figure 3.1 is set-up for a target system with two components. Additional components are added by replicating the last two lines of the input file format. To assemble a batch run input file the entire data structure is repeated. In other words a batch run with two simulation descriptions would include at least 14 lines of data (assuming single plate targets).

4.0 MPPM3 OUTPUT

The MPPM3 output is written to an ASCII data file whose name is supplied by the user and includes the extension ".out". All of the input data is included in the data file for reference prior to the penetration result data. All of the standard data printed to the output file are described in Table 4.1.

Table 4.1: MPPM3 Standard Output Data Summary

Parameter	Units	Definition
X, Y, Z - Impact Coordinates	[in]	For determination of impact yaw and presented area, impacts are presumed to occur when the projectile mass centre reaches the mid-point of plates and types V1 and V2. The projectile presented area at the mid-point of V2 components is used to compute the velocity decay over the entire length of the component (VLOS). Impacts for V3 and V4 components occur at the mid-point of the first plate in the component.
OBL - Impact Obliquity	[deg]	The effect of trajectory deviations from the z-axis on impact obliquity.
YAW	[deg]	Projectile yaw at the impact location.
LAMDA		Ratio of maximum impact bending stress to projectile material ultimate strength. The projectile is presumed to break when LAMDA exceeds a critical value (λ=1), and the residual mass and length are reduced by a factor of 2.
Mr	[grains]	Projectile residual weight behind the current target element.
BETA	[deg]	The angle between the pre-impact projectile trajectory and the post-impact trajectory. BETA is measured in the obliquity plane formed by the pre-impact velocity vector and the plate normal.
Vr	[ft/sec]	Projectile residual velocity behind the current target element.
V50	[ft/sec]	Ballistic limit velocity for current target element computer in RV.
VRV	[ft/sec]	Projectile residual velocity for thin plates computed in RV.
VTPPM	[ft/sec]	Projectile residual velocity for thick plates computed in TPPM.
Nose Diameter	[in]	Projectile nose diameter behind the current target element.
Projectile Length	[in]	Projectile length (total) behind the current target element.
Normalised Projectile Momentum Change		Change in projectile momentum through the target normalised by the pre-impact projectile momentum. A value of 1 indicates the projectile has been stopped by the target.

If the user opts to use the thick plate or combined penetration models (see Section 2.3) the MPPM3 software will prompt them to supply a TPPM output file name to which the extension ".prt" is appended. This additional output file provides a time history of the target system penetration process. The data included in this file is defined in Table 4.2.

Table 4.2: TPPM Output Data Summary

Parameter	Units	Definition
T	[μsec]	Time base for the penetration history description
P	[in]	Position of projectile leading edge referenced to position at time of impact
TP	[in]	Remaining thickness of target plate to be penetrated
GAM		Plate breakout parameter (e.g. GAM = 1 when breakout / penetration occurs)
L	[in]	Residual projectile length
V	[ft/sec]	Projectile residual velocity
U	[ft/sec]	Velocity of projectile / target interface
W	[ft/sec]	Target plug velocity

Since the source code is available, it would be possible to modify the output code to provide a customised output data file format.

5.0 SOFTWARE DESCRIPTION - STRUCTURE AND OPERATION

The following sections provide a technical description of the MPPM3 software and how it operates. The software code is written in standard Fortran 77 and compiled with Microsoft Fortran 5.0. It includes separate I/O and computational engine modules allowing for both interactive and batch run operation. While the computational engine containing the MPPM3 ballistic penetration model is of primary interest to this review, a brief description of the I/O module is provided in the next section followed by a more detailed description of the MPPM3 computational engine.

5.1 MPPM3 I/O Module

The MPPM3 software includes an interactive data entry and file handling pre-processor which operates in a text mode. This module of the MPPM3 software prepares input files for the main computational engine and including subroutines that can generate data files with the previously described default penetrator, encounter and target array data. The remaining subroutines within this first module of the MPPM3 software control the formatting within the program, that is, controlling on-screen cursor movements, text attributes, colours, and menu displays.

Menu options contained in the pre-processor module are used to prompt the user to direct the operation of the software. The main menu controls such options as: loading data from disk, saving data to disk, editing the current data, displaying the current data, running the penetration model, viewing the output results, and exiting the program. Once the user is satisfied with the penetrator, encounter and target array data, the MPPM3 subroutine is called. The subroutine calls or relationships between the various modules of the MPPM3 engine are described in the following section with both a description of the program architecture and a pseudo code description of the code.

5.2 MPPM3 Computational Engine Architecture

The architecture of the MPPM3 software is described in Figure 5.1 which illustrates the relationship between the MPPM3 modules. While the MPPM3 module relationship tree structure looks relatively busy it is made up of 13 basic modules including the MPPM3 mainline. Figure 5.1 illustrates the subroutine calls for the MPPM3 program.

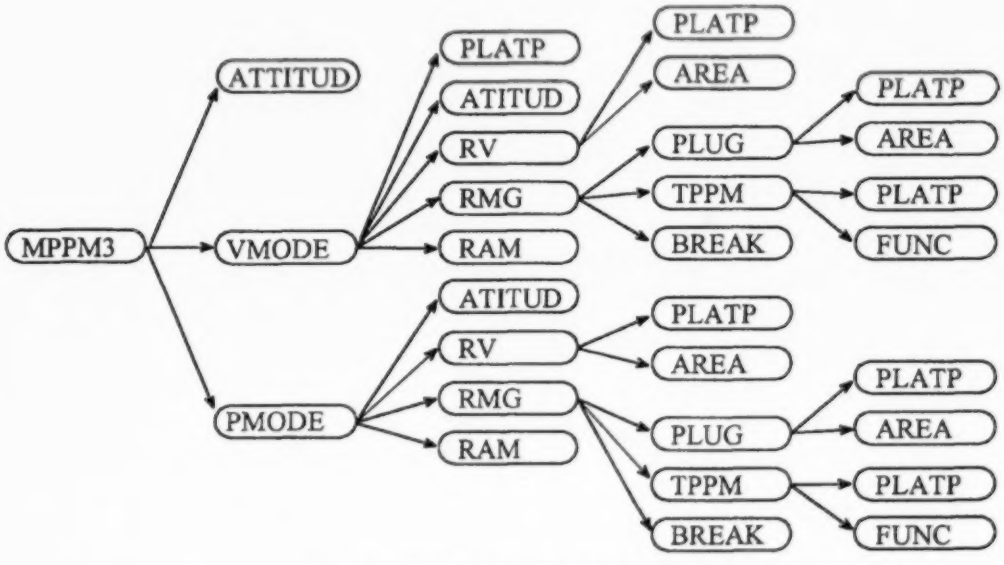


Figure 5.1: Subroutine Calls in MPPM3

5.3 MPPM3 Computational Engine Pseudo Code Description

5.3.1 Subroutine MPPM3

Provides user interface, reads and prints input data, assigns initial values, assigns penetration results behind each plate to the output matrix.

1 – Set initial conditions.
2 – Initialise off-shot line displacement and velocity components. Initial impact presumed to occur on z-axis.
3 – Compute equivalent cylinder dimensions to preserve mass and axial moment of inertia.
4 – Initialise ceramic-hit flag and post-ceramic plate counter.
5 – Enter main do-loop to compute penetrator status after each impact. While I ≤ IPLATE, do:
    1 – Fill output matrix with penetrator values in front of and behind the first plate and behind all remaining plates.
    2 - IF PTYPP = V3 or V4, then reset impact conditions to mid-point of first plate. ENDIF
    3 - Set previous target element type in order to print z-co-ordinate of first plate for V3 and V4 components.
    4 - Exit computational loop when CM or V is zero or exit conditions have been stored in out array.
        1 - IF CM ≤ 0 or V ≤ 0, then IPLATE = I.
        2 - IF I = IPLATE, then CONTINUE to 5 of main do-loop.
        3 - IF I = NPLATE + 1, then determine exit location and direction. ***CALL ATITUD***
        4 - ENDIF

5 - Select proper penetration methodology - Volume or Plate
1 - IF PTYP = V, then ***CALL VMODE***
2 - ELSE, then ***CALL PMODE***
3 - ENDIF
6 - Reset parameters for next impact. CONTINUE
6 – Print output results.
7 – Print out the normalised projectile momentum change.

5.3.2 Subroutine ATITUD

Computes change in projectile attitude between plates.

1 – Compute azimuth and elevation of angular momentum vector and cone angle of penetrator.
2 – Compute current precession angle and new value for next impact.
3 – Compute direction cosines and yaw of penetrator at next impact.
4 – Compute direction cosines of transverse angular velocity at next impact.

5.3.3 Subroutine VMODE

Supervises penetration calculations for volume mode components.

1 – IF PTYP = V1, then
1 - Specify hardness of equivalent plate (needed only for steel and aluminium plates).
1 - IF PMTL = AL, then PBHN = 120.0
2 - IF PMTL = ST, then PBHN = 150.0
2 – Assume equivalent plate obliquity defined by entrance obliquity. Assume y-z plane is obliquity plane.
3 – Compute normal thickness of equivalent plate.
4 – Determine impact co-ordinates, yaw, and obliquity at z-co-ordinate of component mid-point.
5 - ***CALL ATITUD***
6 - ***CALL RV***
7 – Check for valid ceramic parameters.
8 - ***CALL RMG***
9 – ***CALL RAM***
2 – ELSEIF PTYP = V2, then
1 - Determine impact co-ordinates, yaw, and obliquity at z-co-ordinate of component mid-point.
2 - ***CALL ATITUD***
3 – Compute areal density of non-coherent materials (lbs/ft^2).
4 - ***CALL RV***
5 – Check for valid ceramic parameters.
6 – ***CALL RMG***
7 – ***CALL RAM***
3 – ELSE – Default: (PTYP = 'V3' and 'V4') volume mode component represented by 15 aluminium plates and 3 steel plates separated by non-coherent material as determined for avionics components.

1 – Get plate density. ***CALL PLATP***
2 – Compute areal density along path through component (lbs/in^2).
3 – Compute total areal density of metallic plates in component plate array.
4 – Compute normal thickness of aluminium and steel plates in representative plate array (inches).
5 - Compute thickness of non-coherent material between metallic plates in representative plate array (inches).
6 – Compute areal density of non-coherent material plates (lbs/ft^2)
7 – Keep track of maximum lambda value while projectile passes through types 'V3' and 'V4' volume mode components.
8 – Accumulate direction change as projectile passes through 'V3' and 'V4' components.
9 – DO IPLT = 1 to 35 (loop through 35 plates of volume mode component)
    1 – IF CM or V = 0, then exit VMODE.
    2 - IF VZ $\leq$ 0, then CONTINUE
        1 - Compute direction cosines for each plate component.
        2 – Set plate material type and normal thickness.
        3 – Determine impact co-ordinates, yaw, and obliquity at z-co-ordinate for this plate.
        4 - ***CALL ATITUD***
        5 – Save impact conditions at first plate for output array.
        6 – ***CALL RV***
        7 – ***CALL RMG***
        8 – Hold maximum value for LAMB in LAMBMX.
        9 – ***CALL RAM***
        10 – Reset parameters for next impact.
        11 – Accumulate direction change for printing when last component type is 'V3' or 'V4'.
4 – ENDIF

5.3.4 Subroutine PMODE

Supervises penetration calculations for a plate element.

1 – Compute projectile co-ordinates, impact obliquity and projectile yaw at z-co-ordinate of plate centre.
2 – ***CALL ATITUD***
3 – ***CALL RV***
4 – Check for valid ceramic parameters.
5 – ***CALL RMG***
6 – ***CALL RAM***

5.3.5 Subroutine RV

Computes projectile residual velocity for thin plates from the impact geometry and by calling PLATP to obtain the necessary ballistic limit constants.

1 – Compute effective value of projectile presented area.
2 – IF PMTL ≠ NM, then
  1 – ***CALL PLATP***
  2 – Compute areal density (lb/ft^2) for flexible materials and ceramic materials.
  3 – Determine if nose shape is sharp or blunt. For blunt nose, the nose diameter (CDN) is equal to the base diameter (CDT). For sharp nose, the ratio of nose diameter to base diameter is less than or equal to 0.5 and the ratio of nose length to the difference between the base and nose diameters is greater than or equal to 1.0
  IF sharp, then set NSHP = 1,
  ELSEIF, set NSHP = 0.
  4 – Determine attack aspect (default ATK = 1).
    1 - IF NSHP = 0 or YAW ≥ 0.175, then ATK = 0
    2 - IF PMTL = ST and CBHN ≤ 560, then ATK = 0
  5 – Attack aspect for ceramics.
    1 - IF PMTL = CW and CBHN ≤ 560, then ATK = 0
    2 - IF PMTL = CK and CBHN ≤ 560, then ATK = 0
    3 - IF PMTL = PW and CBHN ≤ 560, then ATK = 0
  6 – Check invalid parameters for a sharp attack against ceramics.
  7 – Blunt attack check. IF ATK = 0 (blunt), then
    1 – Compute VX.
    2 – IF PMTL = GR, DO, KV, XP or LX (flexible materials), then compute V50 and VX.
    ENDIF
    3 - IF PMTL = CW, CK, or PW (ceramics), then compute V50 and VX.
    ENDIF
    4 – PMTL = ST or AL (by default), then
      1 – Compute plug-shear component ballistic limit velocity.
      2 – Compute V50 and VBLX for blunt attack.
      3 – Replace VXN by V50N when V < V50N or VXN > V50N.
    5 – Compute change in direction (in obliquity plane toward plate normal).
  8 – ELSEIF ATK ≠ 0 (sharp), then
    1 – Compute VBLX.
    2 - IF PMTL = GT, DO, KV, XP or LX (flexible materials), then compute V50 and VX.
    3 - IF PMTL = CW, CK, or PW (ceramics), then compute V50 and VX.
    4 – ELSEIF PMTL = ST or AL (by default), then compute V50 and VLBX.
  9 – Invoke simplified ricochet model.
  10 – Compute effective plate plug mass for residual velocity calculation. ***CALL AREA***

3 – ELSEIF PMTL = NM, then compute velocity loss through non-coherent material. Note that areal density is used instead of thickness. Assume no direction change for these materials.
4 – Compute residual velocity components.

5.3.6 Subroutine RMG

Computes projectile residual mass, velocity and geometry. An interpolation scheme is used for impacts at intermediate velocities against plates of intermediate thickness when the combined model is selected.

1 – For non-coherent material, projectile is assumed rigid.
IF PMTL = NM, exit subroutine RMG
ENDIF
2 – Neglect erosion/extrusion-shear mass loss when projectile ricochets.
3 – Use plate plug model if selected by user, or if the plate material is a ceramic.
IF TMODEL = P or PMTL = CW or CK or PW, then ***CALL PLUG***
ENDIF
4 – Use TPPM model if selected by user. Add ceramic material parameters to TPPM call statement.
IF TMODEL = T, then ***CALL TPPM***
ENDIF
5 – Select combined model (default).
6 – ***CALL PLUG*** to compute mass loss against thin plates at high impact velocities.
7 – Use TPPM to compute mass loss against thick plates of against thin plates near the ballistic limit velocity.
8 – Use TPPM for mass loss at or below the limit velocity or well above the hydrodynamic transition velocity.
IF $V \leq V50$ or $V \geq 2.5VHD$, then ***CALL TPPM***
ENDIF
9 – Use TPPM and interpolation equations for mass loss at intermediate velocities. Use plate plug velocity here.
10 – Modify transition formula to yield CMR = CMRT1 at V = 2.5*VHD
11 – Use PLUG and TPPM and interpolation formulas for mass loss against plates of intermediate thickness or against thin plates at intermediate velocities.
12 – Recalculate residual velocity for thick plates when impact velocity is greater than limit velocity.
13 – Determine if projectile broke. ***CALL BREAK***
14 – Calculate residual nose shape.
15 – Recalculate equivalent cylinder size when part of nose remains.

5.3.7 Subroutine PLUG

Computes residual mass, length and diameter of the penetrator as functions of the plate and penetrator material properties, plate thickness and the pre-impact mass, length, diameter, velocity, yaw and obliquity of the penetrator.

1 – ***CALL PLATP*** to obtain plate properties.
2 – Use presented area of equivalent cylinder to determine length and diameter of equivalent unyawed cylinder.
3 – Compute thickness of equivalent normal plate.
4 – Use effective area and plate impact factor to determine effective rigid plug mass. ***CALL AREA***
5 – Compute remaining length, mass and velocity of equivalent cylinder after shock phase.
6 – Compute undeformed length of equivalent cylinder.
7 – After deformation phase – neglect deformation mass loss in thin aluminium plates.
8 – Compute estimate of CJ*TTAU and use Newton-Raphson method to determine TTAU.
9 – Compute mass, length and diameter of equivalent cylinder after deformation phase.
10 – Convert residual mass, length, and diameter to equivalent values for the yawed cylinder.

5.3.8 Subroutine RAM

Computes projectile residual angular momentum after each impact.

1 – Compute components of velocity change.
2 – Set constant relating linear and angular momentum changes and compute components of change in angular momentum of residual penetrator.
3 – Compute pre-impact moments of inertia and pre-impact angular momentum components of residual penetrator.
4 – Compute moments of inertia and angular momentum components of residual penetrator.

5.3.9 Subroutine PLATP

Contains plate parameters (see Section 4.7 for plate material properties)

1 – Determine plate material and compute or assign appropriate material properties.

5.3.10 Subroutine BREAK

Determines projectile break-up.

1 – Break-up calculation for ricochet.

5.3.11 Subroutine AREA

Computes effective plate plug cross-sectional area.

1 – Computes effective plate plug cross-sectional area.

5.3.12 Subroutine TPPM

Determines equivalent, unyawed, cylinder dimensions, introduction of the minimum interface velocity for applications to thin plates, introduction of the extrusion/shear mass loss computation, and elimination of the debris model.

1 – ***CALL PLATP***
2 – Use presented area of equivalent cylinder to compute length and diameter of equivalent unyawed cylinder.
3 – Calculate dimensionless parameters for TPPM.
4 – Calculate flow stress for unconfined plate material (uniaxial stress).
5 – Set initial values for penetration flags.
6 – Set initial values for dependent variables.
7 – Set initial interface velocity. Avoid interface velocity less than 0. Avoid divide by 0 when plate and projectile identities are equal. Avoid interface velocities greater than projectile velocity and avoid negative square roots.
8 – Integrate penetration equations using fifth-order Runge-Kutta procedure. ***CALL FUNC***.
9 – Kinematic constraints on projectile, interface, and plug velocities. If length becomes negative or zero, equate projectile and interface velocities to plug velocity.
10 – Flow stress in plate corresponds to uniaxial stress conditions (i.e., permit plug to continue erosion beyond breakout). New flow stress value assigned in FUNC.
11 – Once deformation has begun, length cannot decrease faster than UCV.
12 – Reassign integration history array values.
13 – Set indices denoting breakout and beginning of deforming and rigid penetrator behaviour.
14 – Redefine CMR when length = 0 in case LEESD and LESD produce non-zero value.
15 – Restore extrusion shear mass loss for aluminium plates.

5.3.13 Subroutine FUNC

Contains the differential penetration equations for thick plate penetration model TPPM.

1 – Constraints are required in FUNC as well as TPPM because of calls to FUNC at intermediate time steps before computing dependent variables. Flow stress in plate corresponds to uniaxial stress conditions (i.e., permit plug to continue erosion beyond breakout). Also, plug shear resistance set to zero after breakout.
2 – Modify and rearrange kinematic constraints on V, U, and W.
3 – Projectile and target defeat criteria.
4 – Allow plug to erode under uniaxial stress after breakout.
5 – Once deformation has begun, length cannot decrease faster than UCV.
6 – Allow plug to erode under uniaxial stress after breakout.
7 – Continuity at beginning of deformation and which recognises combined effects of enlarged frontal area of deformed penetrator and that all plate material in path of penetrator is not accelerated to velocity U.
8 – Allow plug to erode under uniaxial stress after breakout.
9 – Define flow factor for when deformation does not occur prior to rigid penetration (will only occur when U = V at T = 0).

6.0 CONCLUDING REMARKS

The Debris Characterisation and Modelling (DeCaM) software was developed to quantitatively characterise experimentally captured BA-debris data and model or predict the characteristics of BA-debris clouds generated in ballistic penetration events. Both the BA-debris characterisation and modelling require information describing the residual penetrator mass and velocity. The Multiple Plate Penetration Model (MPPM3) software was adopted by DeCaM to estimate residual penetration characteristics.

The Multiple Plate Penetration Model (MPPM3) software and its documentation were reviewed with a to develop a better understanding of its: data requirements, output formats, operation and limitations. Based on this review:

- it was noted that target and projectile material properties were embedded in the software,
- many parameters used in the MPPM3 software to predict projectile penetration behaviour are regressed modelling constants without physical meaning,
- the MPPM3 input data files are logically arranged and may be assembled by DeCaM, and
- the output files produced by MPPM3 contain all of the information required for DeCaM and are arranged in a logical format from which information may be automatically drawn.

In general, the MPPM3 software was found to be a useful modelling tool and a valuable addition to the DeCaM software. Further information concerning the validation of the DeCaM software including MPPM3 is outlined in the project report.

7.0 REFERENCES

Yatteau,J.D., Zernow,R.H., Recht, R.F., "Compact Fragment Multiple Plate Penetration Model(FATEPEN2)." Vol. I – Model Description, Vol. II – Computer Code User's Manual, NAVSWC TR 21-399, Applied Research Associates, Inc., Lakewood, CO, 1991b.